IBOC DAB will facilitate radio's ability to continue to play this role even as radio transitions to a digital environment. Because IBOC allows stations to transmit both analog and digital signals, listeners will continue to be able to use analog radios for many years. Thus, the public will continue to have access to this source of emergency alert information during the transition to digital radio. If all existing receivers were immediately rendered obsolete by a new digital radio service, it is likely that portions of the population would be left without a link to the EAS. IBOC DAB will also help protect the EAS by upgrading broadcast radio and thus promoting the continued viability of AM and FM radio broadcasting. To the extent that listeners are drawn away from radio to other sources of news, information or entertainment (pre-recorded music, cable delivered radio, satellite DARS) which are not participants in the EAS, the government loses a vital means to alert the public. Thus, the authorization to implement IBOC DAB will only strengthen the EAS.

## V. SYSTEM REQUIREMENTS FOR TRANSITION TO DIGITAL

Based on the above analysis of the existing environment in the AM and FM bands, USADR sets out below a number of fundamental system requirements for its IBOC DAB system. Although a system could provide exceptional performance in any one area, USADR believes that the optimized system which will best serve the public interest must correctly balance these various system attributes.

A. General IBOC DAB Requirements

*Audio Quality*

To achieve enhanced audio quality, a DAB system must deliver a new listening experience to the public. For FM, USADR refers to the improved level of sound quality as "virtual CD-quality." For AM, USADR uses the term "FM-quality" or "FM-like" to describe the attainable level of quality equivalent to current analog FM. Enhanced audio quality is also achieved through improved robustness which results in higher immunity to signal fading, noise, and impairments.

*Compatibility*

System compatibility requires that the DAB system take into account both the limitations imposed by the existing transmission environment and the modes of reception of AM and FM radio. The system must be able to operate in an environment with significant co-channel and adjacent channel sources of analog and digital interference. The system must also operate without noticeably increasing interference to host co- and adjacent channel analog transmissions.

*Coverage*

The IBOC DAB system must provide service to the existing analog coverage area, while maintaining compatibility with the existing AM and FM broadcast infrastructure. Coverage must take into account actual station coverage based on geographic and interference limitations. In many cases, actual coverage differs from the coverage that can be predicted based on the Commission's rules.

*Analog Reception*

The IBOC DAB system should improve broadcasting not only through the digital signal, but also for AM and FM analog reception. IBOC DAB receivers are implemented in digital circuitry where there is low (or no) marginal cost to improve analog reception when operating in the hybrid mode. Reception is improved because rejection of the adjacent channel interference is greater and noise for the analog signal is lower.

*Auxiliary Services*

Existing FM subcarrier services should be upgraded in the transition to DAB. The IBOC DAB system provides for auxiliary data and audio services which will essentially upgrade the services currently offered using existing FM subcarriers.

*Flexibility*

The transition from analog to digital has the potential for consumer confusion and disruption if not properly managed. Although IBOC technology is inherently more flexible than a non-IBOC solution, the IBOC system should be designed to maximize listener and broadcaster flexibility in order to allow market forces to guide the transition.

*Cost*

Both broadcasters and listeners will need to acquire new equipment in order to implement DAB. The IBOC DAB system should be designed to permit much of this capital investment to be made in the normal course of equipment replacement cycles if the broadcaster or listener so chooses. Reasonable conversion costs should also be emphasized.

*Graceful Degradation*

As a digital receiver approaches the edge of coverage, its signal quality deteriorates abruptly. In fact, audio quality can change from virtually unimpaired to non-existent almost instantly. This "all-or-nothing" quality drop-off could annoy listeners who are accustomed to graceful analog degradation (or perhaps even cause them to suspect equipment malfunction). As a result, the IBOC DAB system should provide a means of gracefully degrading the signal as the edge of coverage is approached or as the signal quality is impaired.

*Channel Acquisition*

Digital receivers that are designed to be robust in a mobile environment typically have extended acquisition times. When a listener opts to change a channel on a digital receiver, there is usually a significant period of time -- perhaps on the order of a few seconds -- before the associated audio is heard. This delay is due to processing that is specific to digital receivers (such as de-interleaving and decoding). The IBOC system should have a means of quickly acquiring the signal upon re-tuning or re-acquisition in a manner that is equivalent to what listeners are used to when tuning between analog stations.

B. <u>Transition Issues</u>

For every radio station, there will be three separate modes of operation. Stations can continue to broadcast in the present analog mode. During the transition period to digital, each station will have the opportunity to upgrade to the second mode of operation -- the hybrid mode. The hybrid mode will support simultaneous transmission of station programming in both analog and digital. At some date in the future, each station will be able to turn off its analog signal and operate in the third mode of operation -- the all-digital mode.

Each broadcast station will decide when it switches from analog to hybrid, and from hybrid to all-digital. As a result, there will be an extensive transition period during which stations will be operating in different modes. In such an environment, it is inevitable that there will be situations where a station operating in any of the three modes will have co-channel or adjacent channel interferers operating in various combinations of analog, hybrid, and digital modes. The IBOC DAB system must ensure all three modes of operation can co-exist.

The IBOC DAB system should provide forward and backward compatibility for listeners. The first digital receivers sold will operate in the interim hybrid phase, as well as the future all-digital environment. DAB receivers will be forward compatible because the digital transmission can be upgraded in the future without rendering obsolete earlier generations of digital receivers. Receivers will also be backward compatible because they can incorporate existing analog technology, permitting continued listening to analog broadcasts. Thus, a listener can make its own decision when to upgrade to hybrid or all-digital

## VI. USADR FM IBOC DAB SYSTEM

### A. System Description

The USADR FM IBOC DAB system is comprised of four basic components: the modem, which modulates and demodulates the signal; the codec, which source encodes and decodes the audio signal; forward error correction ("FEC") coding and interleaving; and blending. USADR has designed and integrated these core functional areas to produce a system which complies with the requirements for IBOC DAB described in Section V above.

USADR evaluated several modulation techniques for the IBOC DAB FM system before selecting Quadrature Phase Shift Keying ("QPSK") QPSK permits robust performance and provides sufficient throughput for virtual CD-quality digital audio. It permits the use of advanced FEC coding techniques which exploit knowledge of the non-uniform interference environment. QPSK is also simpler and more robust than higher-order forms of modulation, particularly in a multipath environment. Since QPSK has a bandwidth efficiency of two bits per second per Hertz, it supports an information bit rate that is sufficient for transmission of virtual CD-quality audio in the bandwidth available.

USADR reviewed whether to use a multi-carrier or single-carrier approach to transmit the digital signal, and chose a multi-carrier approach called Orthogonal Frequency Division Multiplexing ("OFDM"). OFDM is a scheme in which many QPSK-modulated carriers can be frequency-division multiplexed in an orthogonal fashion such that each carrier does not interfere with each adjoining carrier. OFDM offers a high level of robustness to multipath.

The FM channel bandwidth does not have the capacity to support a sufficiently high data rate to provide virtual CD-quality audio without some form of compression. As a result, an audio codec (coder-decoder) must be employed to overcome these bandwidth limitations. USADR uses the MPEG AAC codec in its IBOC DAB systems. The AAC codec compresses a digital bit stream to 96 kbps, delivering audio that the listener will perceive to be virtually the same quality as a CD. Use of the AAC codec meets the raw throughput requirement of the modulation and FEC coding techniques. In addition, special error concealment techniques employed by the codec help to ensure graceful degradation of the received digital signal. In addition to its ability to meet the USADR system's audio compression requirements, MPEG AAC offers the advantage of being an open system based on the MPEG family of ISO standards.[59]

FEC and interleaving greatly improve the reliability of the transmitted information. Advanced FEC coding techniques introduce codes into the transmitted digital signal to reduce lost information. Special interleaving techniques spread errors over time and frequency to assist the FEC decoder in correctly decoding of the transmitted signal. This combination, together with superior modem performance, increases the robustness of the signal to allow the IBOC DAB system to deliver virtual CD-quality audio beyond the FCC-protected signal strength contour in both fixed and mobile environments.

The USADR system employs time diversity between two independent transmissions of the same audio source to provide robust reception during the outages that are typical in a mobile environment. When the primary digital signal is corrupted, the receiver blends to the backup audio which, by virtue of its time diversity with the primary signal, does not experience the outage. The blend feature also provides a means of quickly acquiring the signal upon tuning or re-acquisition.

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[59] Additional information on the AAC codec and the advantages of the MPEG family of audio compression standards is contained in Appendix J.

1. Hybrid mode

The FM hybrid mode of operation is shown in Figure 2. Low-level digital sidebands are added to each side of the analog signal. These digital sidebands provide the "primary digital service." USADR has conducted simulations and analyses[60] which verify that restricting the digital carriers to the 70-kHz regions between 129 and 199 kHz from the center frequency on either side of the analog spectrum minimizes interference to the host analog and adjacent channels without exceeding the Commission's existing spectral mask. This bandwidth is wide enough to support a robust hybrid IBOC service that mirrors the coverage area of existing radio stations. The dual-sideband OFDM structure also enables the use of frequency diversity to further combat the effects of multipath fading and interference.

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[60] *See* Appendix E.

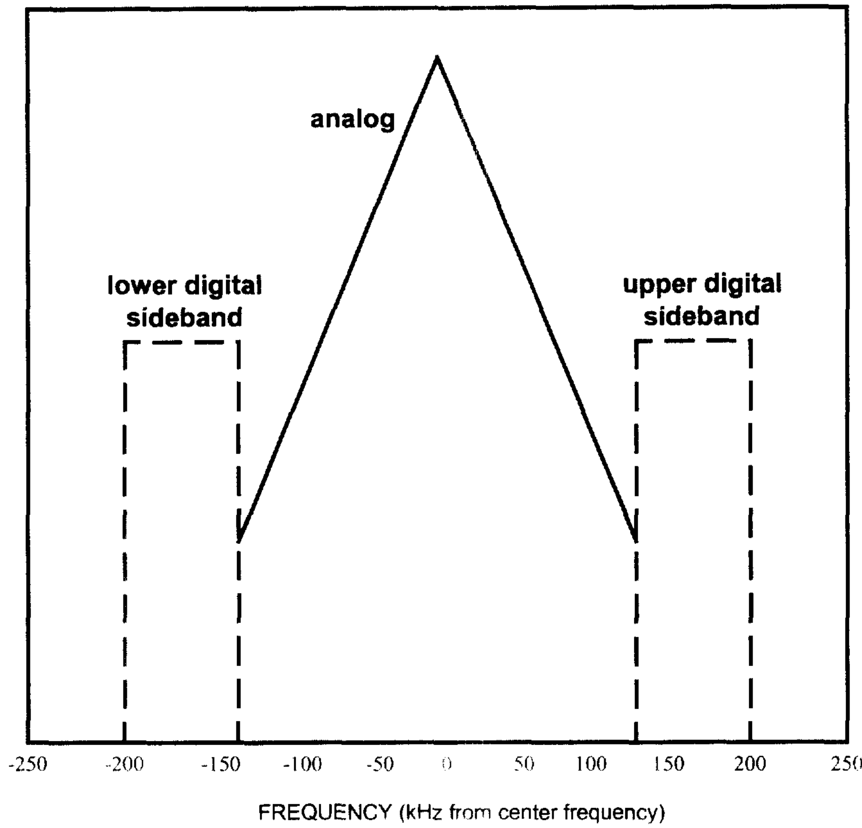


**Figure 2 – Hybrid FM IBOC Signal**

2. <u>All-digital mode</u>

The all-digital mode differs from the hybrid mode primarily through deletion of the analog signal at the center of the channel, leaving the two digital sidebands, as shown in Figure 3. The power of the sidebands is increased, making them more robust than the hybrid mode DAB sidebands; however, each remains within the current FCC spectral mask. The number of OFDM carriers is also increased such that each sideband occupies a bandwidth of 100 kHz. The additional 30 kHz in each sideband carries backup audio, additional auxiliary services, or additional FEC overhead. Low-level OFDM carriers added to the central 200-kHz region can support multichannel sound or enhanced auxiliary services. These carriers support the secondary digital services.

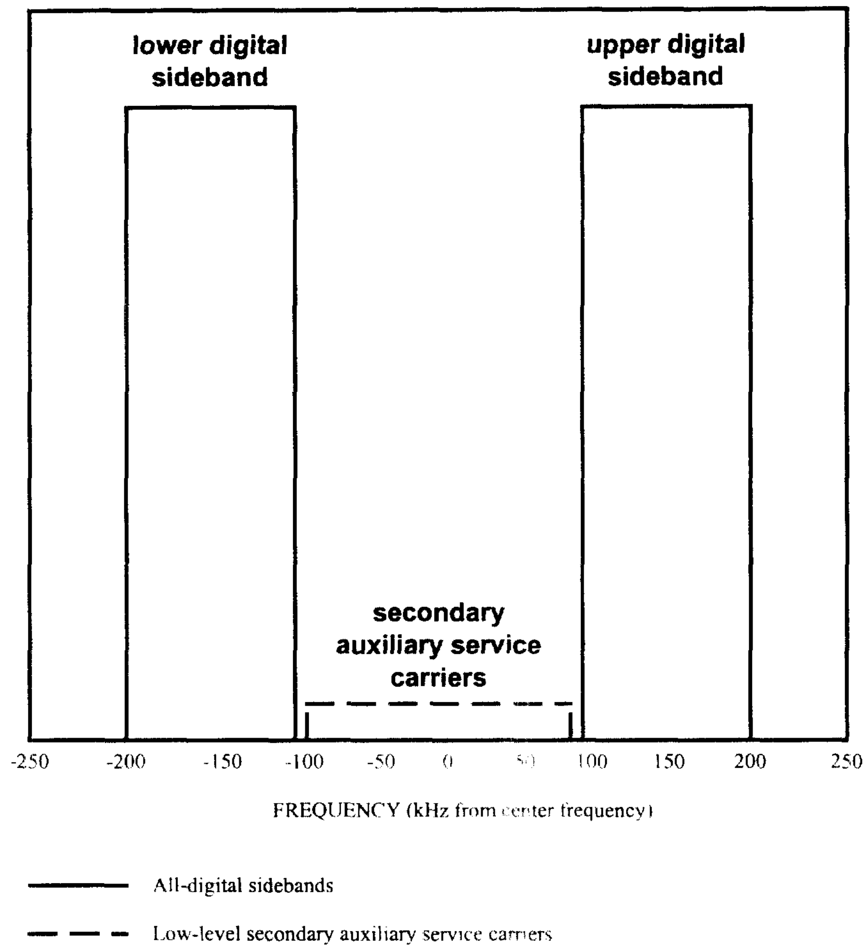


**Figure 3 – All-Digital FM IBOC Signal**

The all-digital mode is similar to the hybrid mode in that the digital signal is split into two sidebands. However, the energy in the all-digital signal is not concentrated around the center of the channel as it is in the existing FM signal. There are a number of reasons for this "split" structure.

First, the split sideband spectrum maximizes compatibility with adjacent channel digital sidebands. The all-digital signal does not interfere with adjacent channel digital sidebands from systems operating in either the all-digital or hybrid modes. This effectively eliminates interference between primary digital services. Second, splitting the signal enables the use of frequency diversity to combat the effects of multipath fading and interference. Third, the dual-sideband format is a natural extension of the hybrid mode. The all-digital mode is virtually identical in complexity to the hybrid mode, and requires little additional receiver processing.

3. Compatibility

During the transition to the all-digital period, analog-only, hybrid, and all-digital stations may exist next to each other on the dial; thus, each must be compatible with the other. Interference, especially digital-to-digital, should be minimized. The USADR IBOC DAB FM system is designed to achieve this result.

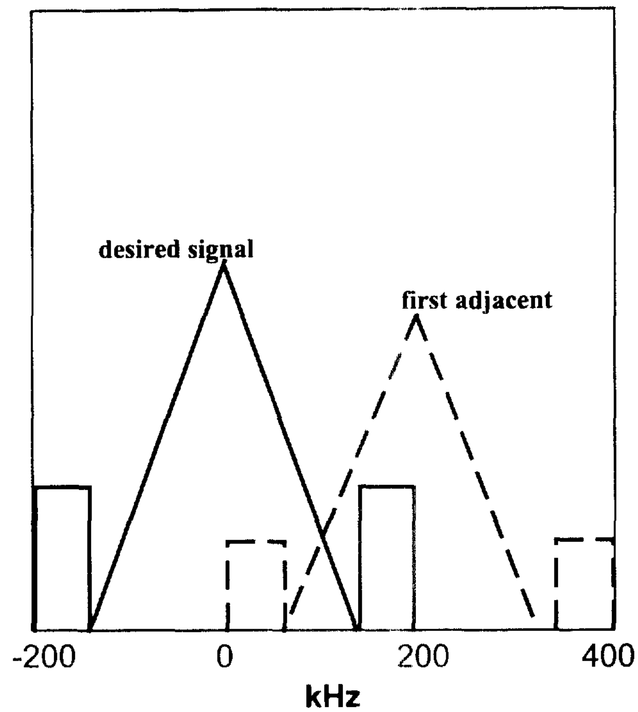


**Figure 4 - Interference scenario showing hybrid first adjacent**

Figure 4 shows a potential scenario in which a desired hybrid signal and an upper first-adjacent hybrid interferer can co-exist. This is a typical interference scenario during the interim hybrid period. The figure shows that there is no interference between the hybrid digital sidebands. However, the analog portion of the first-adjacent hybrid signal interferes with the upper digital sideband of the desired hybrid signal In an effort to reduce analog interference to the digital sideband, USADR has developed a technique known as First Adjacent Cancellation ("FAC").[61] In addition, the use of frequency diversity and advanced FEC coding techniques further improve the performance of the desired digital signal under these conditions.

[61] *See* Appendix F for performance results with FAC

Figure 4 also shows that adjacent hybrid digital sidebands may increase the noise level in the analog portion of the desired hybrid signal. However, in typical receivers, this interference should be no worse than that currently engendered by first adjacent analog signals.[62]

USADR's system is designed so that hybrid and all-digital signals are compatible. Figure 5 shows a potential scenario in which a desired all-digital signal and an upper first-adjacent hybrid interferer can co-exist. As in Figure 4, the analog portion of the first adjacent hybrid signal interferes with the upper digital sideband of the desired all-digital signal. Since the all-digital sidebands will have more power than the hybrid sidebands, the all-digital signal will be more robust than the hybrid signal when subject to this same level of interference.

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[62] *See* Appendix E, Section 4.2.1.2 for a detailed analysis of this issue.

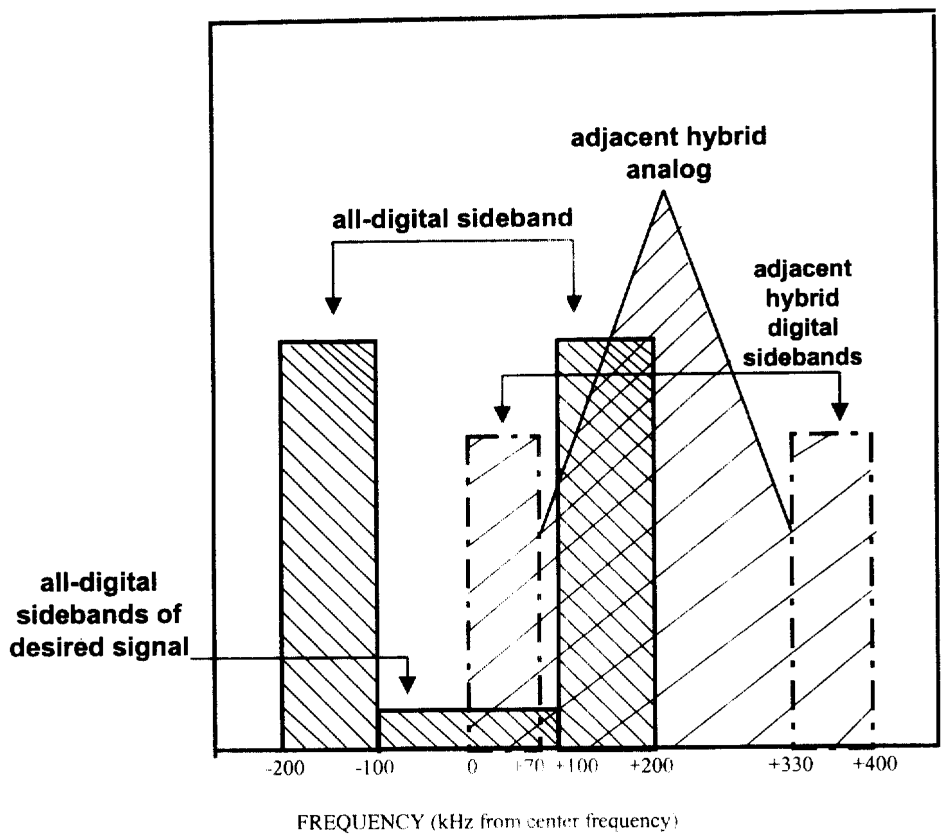


**Figure 5 - Hybrid and All-Digital Compatibility**

Figure 5 also shows that the upper digital sideband of the desired all-digital signal interferes with the desired analog portion of the adjacent hybrid signal. However, broadcast of the higher-powered all-digital signal is not permitted during the interim hybrid period. After then, there will be many IBOC DAB receivers that will receive the interference-free digital transmission. The all-digital signal has been designed to protect newly introduced DAB receivers, rather than older analog receivers; therefore, the digital-to-analog interference is not a primary concern. Note that this analysis also applies to analog-only, rather than hybrid, interfering signals.

The USADR design ensures that the newly introduced primary digital services do not interfere with each other. This is illustrated in Figure 5 which shows that the upper sideband of the all-digital signal does not overlap with the lower sideband of the first-adjacent hybrid signal. Note that there is an overlap between the low level carriers used for secondary auxiliary services in the desired all-digital signal and the lower digital sideband of the first-adjacent hybrid signal. Although the acceptable power level of the low level carriers precludes interference to primary digital sidebands of adjacent channel signals, the low level carriers are still subject to interference from them.[63] Advanced FEC coding techniques help to overcome this interference. Although the carriers used for secondary services do not enjoy the same coverage area and robustness as the all-digital primary sidebands, acceptable levels of performance are achievable within the station's protected contour, except in the presence of two large first-adjacent signals.

[63] *See* Appendix A for proposed rule 73.325 which provides protection for the primary digital sidebands from the secondary auxiliary services.

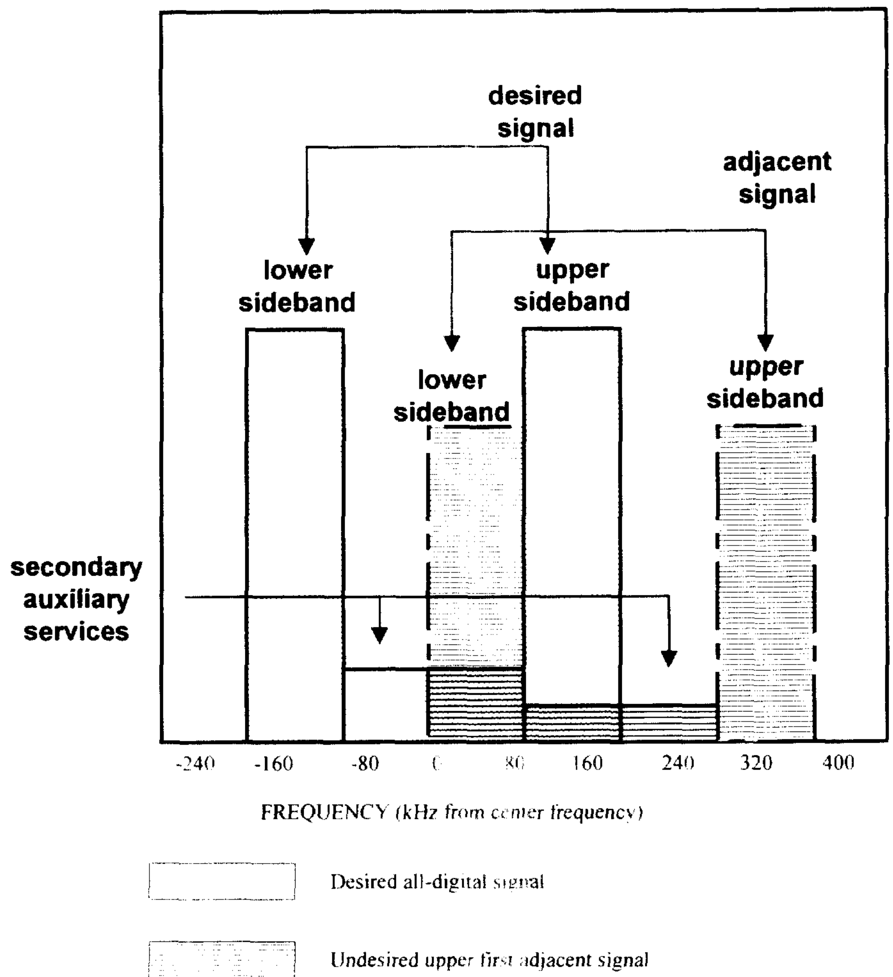


**Figure 6 - All-Digital Compatibility**

Finally, during the all-digital period, the USADR IBOC DAB design ensures adjacent all-digital signals can co-exist. Figure 6 shows a scenario in which a first-adjacent all-digital signal resides next to a desired all-digital signal. As discussed above, there is no interference between primary digital services; the upper desired sideband in Figure 6 does not overlap with the lower sideband of the first adjacent signal. Likewise, the secondary auxiliary services of the desired signal are too low in power to interfere with the primary lower digital sideband of the first adjacent signal. The lower sideband of the first-adjacent signal does interfere with the secondary auxiliary services of the desired signal, which, as discussed above, will nonetheless achieve acceptable performance.

Because there is no overlap of digital sidebands when all broadcasters are transmitting in the all-digital mode, adjacent-channel interference between primary services will be eliminated. The sidelobes of the all-digital and hybrid sidebands are minimized by employing special sidelobe reduction techniques in the modulator. In addition, USADR is working closely with transmitter manufacturers, who can produce transmitters with sufficient sidelobe attenuation to protect adjacent channels.

4. FM IBOC Signal Generation

A functional block diagram of a hybrid mode FM IBOC DAB transmitter is presented in Figure 7. The sampled stereo audio source feeds both the analog and DAB signal generation paths. A diversity delay is introduced in the analog path for blend to backup audio purposes. In the power combiner method shown here, the audio is processed and delivered to the analog exciter for amplification by the high power amplifier ("HPA").

First, the DAB path source encodes the audio signal in the audio encoder. To ensure that the broadcast of information through the fading channel is robust, the compressed bit stream is then passed through the FEC coding and interleaving function. The resulting bit stream is packaged into a modem frame and QPSK- and OFDM-modulated to produce the DAB baseband signal. This baseband signal is upconverted and amplified before being power combined with the analog signal.[64]

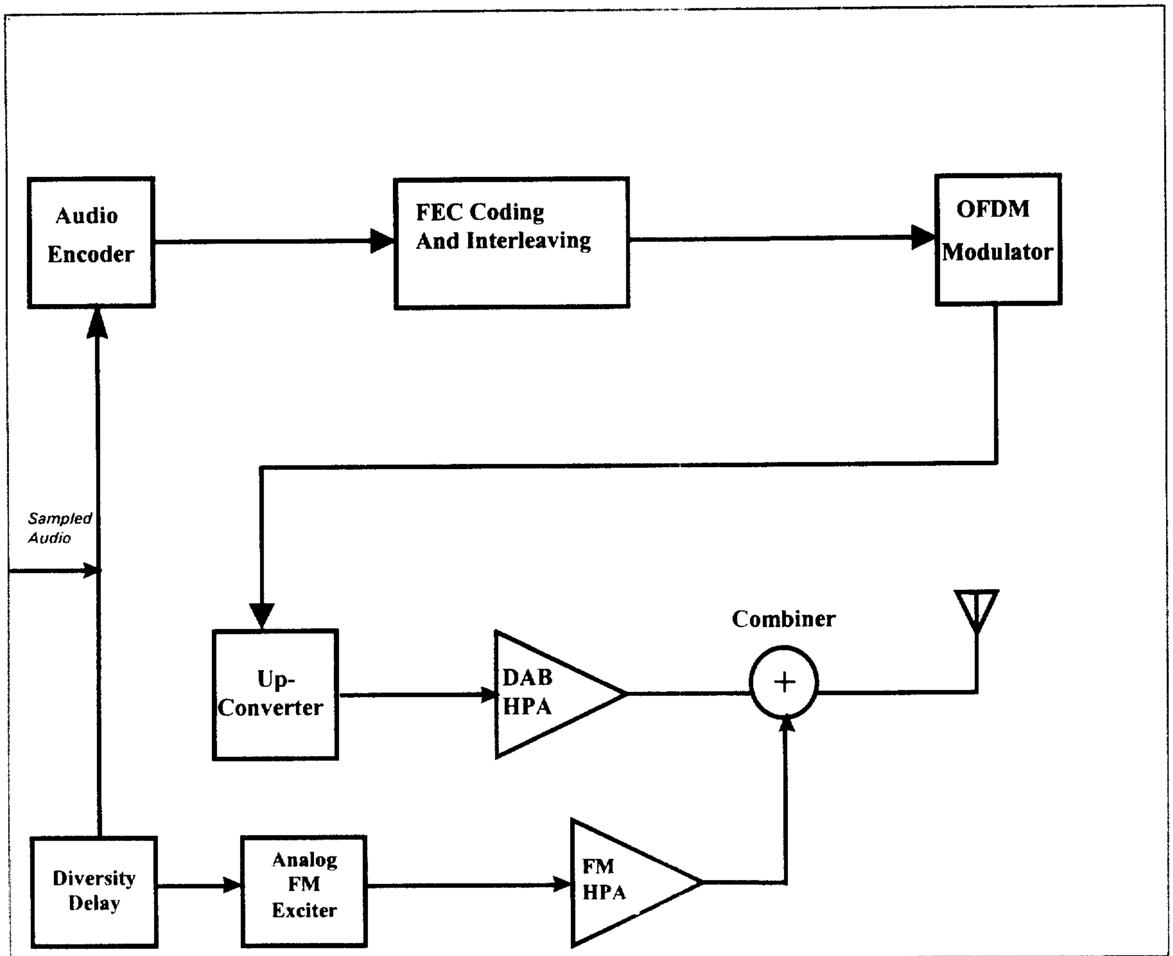


**Figure 7 - FM IBOC Hybrid Transmitter Functional Block Diagram Showing Power Combiner Method**

As shown in Figure 8 below, the all-digital transmitter replaces the analog signal path with a shorter interleaver and FEC.

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[64] Details such as data insertion and FM/DAB blend synchronization have been omitted here for simplicity.

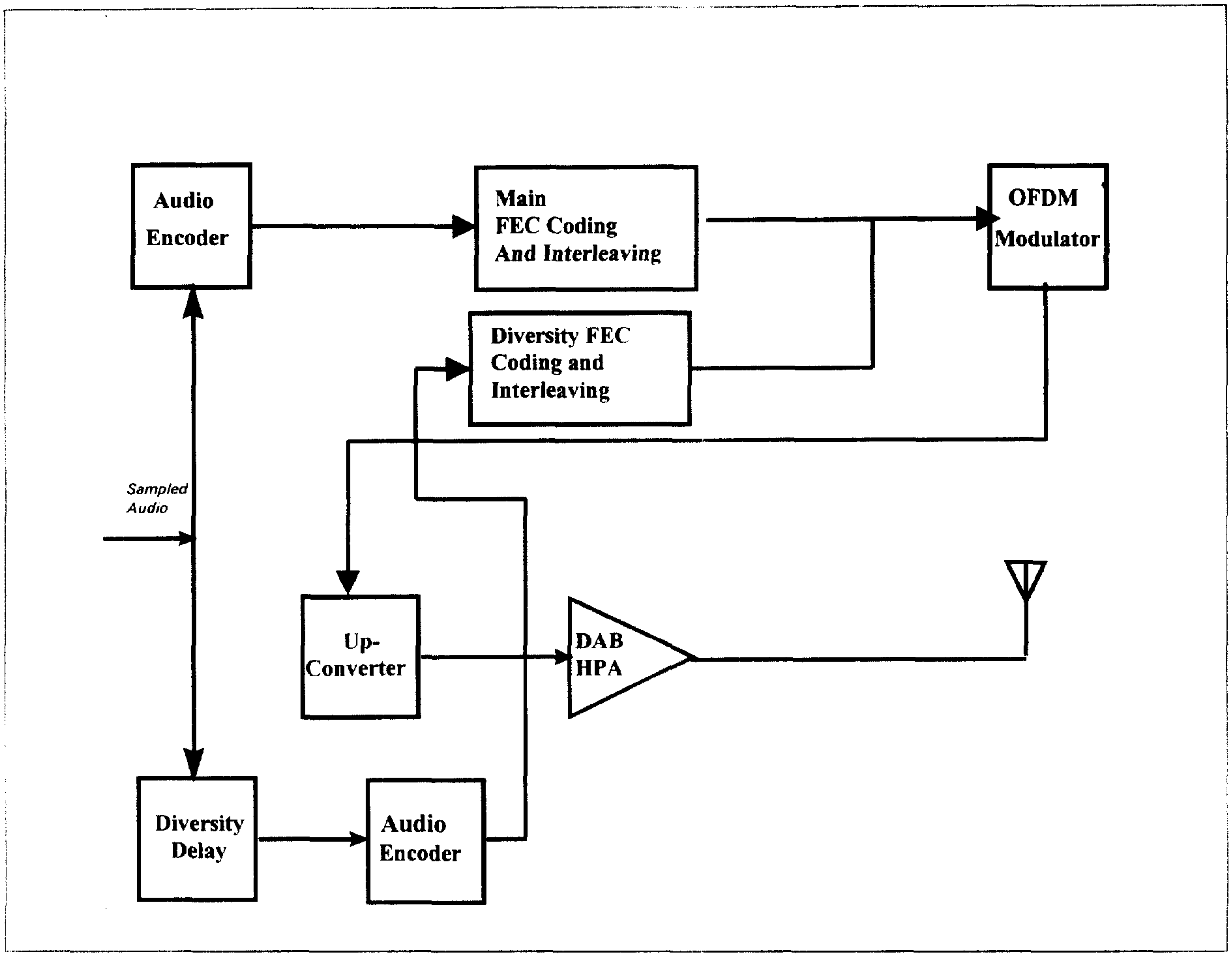


**Figure 8 - FM IBOC All-Digital Transmitter Functional Block Diagram**

5. FM IBOC Signal Reception

USADR IBOC DAB receivers will be backward and forward compatible: they will receive both analog and digital broadcasts in the interim hybrid period, and will be fully compatible with the future all-digital period.

A functional block diagram of an FM IBOC receiver is presented in Figure 9. The signal is received by the antenna, passed through an RF front end, and mixed to Intermediate Frequency ("IF"), as in existing analog receivers. Unlike typical analog receivers, however, the signal is then digitized at IF, and digitally down-converted to produce in-phase and quadrature baseband components. The hybrid signal is then separated into an analog FM component and a DAB component. The analog FM stereo signal is digitally demodulated and de-multiplexed by the FM receiver to produce a sampled, stereo audio signal.

The baseband DAB signal is first sent to the modem, where it is processed by the FAC to suppress interference from potential first-adjacent analog FM signals. The signal is then OFDM demodulated, deframed, and passed to the FEC decoding and de-interleaving function. The resulting bit stream is processed by the codecs to decompress the source-encoded main digital back-up audio signals. These signals are then passed to the blend function.

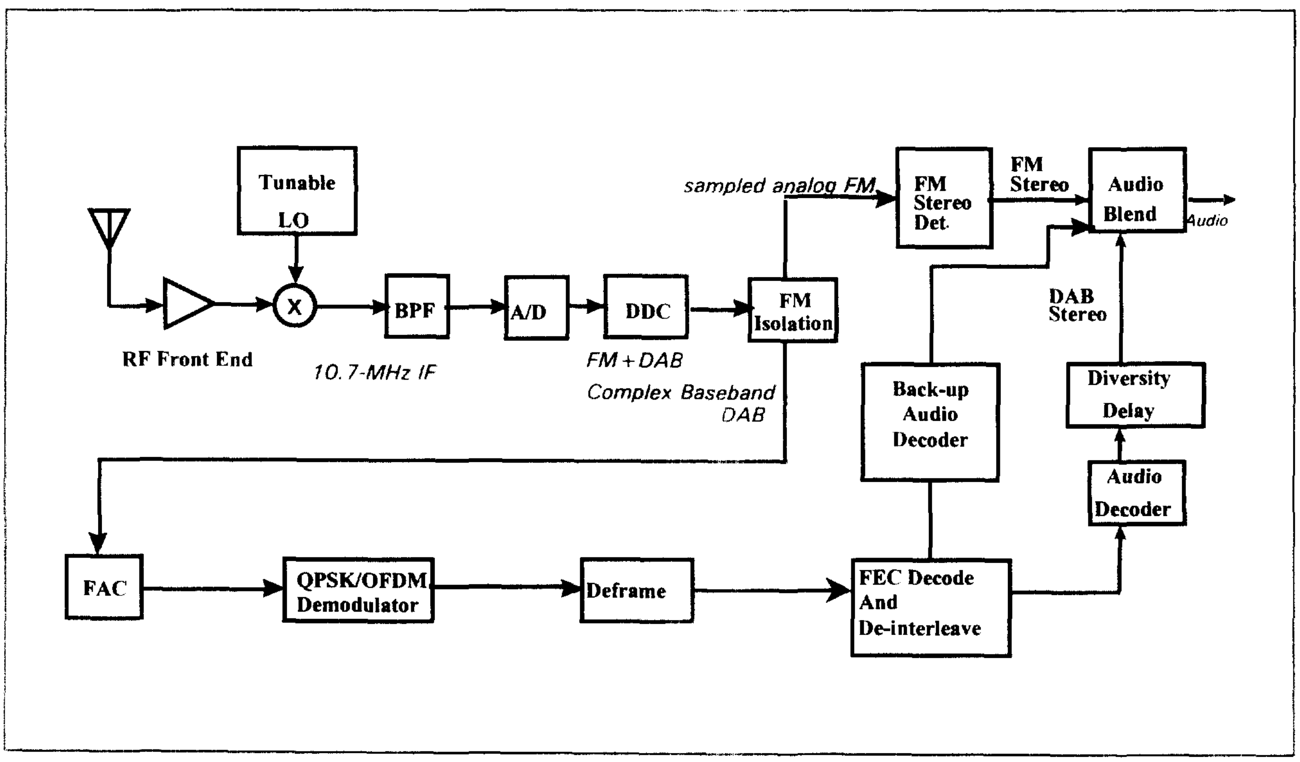


**Figure 9 - FM IBOC Receiver Functional Block Diagram**

## B. FM System Performance and Compatibility[65]

### 1. Introduction

IBOC DAB system performance is dependent on several factors, including power, bandwidth, and spectral placement of the digital sidebands. USADR has balanced these factors to mutually optimize digital system performance, analog compatibility and audio quality.

To verify that the resulting design is indeed capable of harmonious co-existence in both current and future environments, the system was modeled and simulated using state-of-the-art computing resources. The computer simulations focused on two areas of compatibility. First, performance of the digital signal in an environment comprised of both existing analog and IBOC signals was examined. This first group of simulations investigated performance of hybrid and all-digital IBOC signals in the presence of various combinations of co- and adjacent-channel analog, hybrid, and all-digital signals. Second, the effects of digital signals on existing analog broadcasts were analyzed. These simulations measured the degradation introduced by appending DAB sidebands to an analog FM signal.

The methodology, simulations, and results were independently verified by recognized electrical engineering experts, Dr. R.L. Pickholtz and Dr. B.R. Vojcic, and are presented in Appendix I.

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65 Appendix E contains a detailed discussion of the results presented below, as well as USADR's methodology and analysis

2. FM IBOC hybrid and all-digital mode performance

A variety of simulations and analyses have characterized the performance of the FM IBOC DAB hybrid and all-digital modes while subject to various combinations of three types of impairments: Gaussian noise,[66] multipath fading, and interference. The simulations determined the margin of the received digital signal at the analog protected contour. This permits comparisons between potential digital coverage and existing analog coverage.

*Gaussian Noise*

These simulations set an upper bound on system performance, and allowed validation of the model. Results indicate that the hybrid signal has a margin of 22.5-dB at the protected contour of a Class B station.

*Multipath Fading*

Simulations were run using four different multipath models, covering a range of vehicle speeds and locations. Results indicate that the hybrid signal has a margin of 9 to 20 dB at the protected contour of a Class B station. These results indicate that the coverage of virtual CD-quality digital audio in a mobile environment will approximately match the coverage afforded by existing analog broadcasts in the same channel.

*Independently Faded Interference*

These simulations were performed in the presence of various combinations of co-channel, first-adjacent channel, and second-adjacent channel interference from analog, hybrid, and all-

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[66] Gaussian noise is used herein as a baseline environment without fading or interference.

digital signals. The simulations modeled a number of interference scenarios, ranging in severity from typical to "worst-case."

Simulations were run in the presence of a single first-adjacent interferer of varying amplitudes. Results indicate that the hybrid signal has a margin of 13 dB at the protected contour of a Class B station.

Conditions were further deteriorated by then placing a second first-adjacent signal on the opposite sideband of the desired signal. Results indicate that, with two high-level first-adjacent interferers which would only be present in a short-spaced scenario (+6 dB D/U[67] on each sideband) the hybrid signal has a margin of 3 dB at the protected contour of a Class B station. Hence, even in an arguably worst-case mobile environment with both digital sidebands impacted by large analog interferers, the system continues to deliver virtual CD-quality digital audio out to a Class B station's protected contour, with margin.

Since there is no direct overlap of energy between the desired digital signal and second-adjacent signals, and since the FCC provides significant protection against co-channel interference, the effect of these types of interference is minimal.

The results described above apply to desired hybrid signals. However, they may easily be extended to all-digital signals. Since the all-digital sidebands enjoy a 10 dB increase in power over the hybrid sidebands, all of the above results are improved by roughly 10 dB for the all-digital system.

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67 D/U is defined as the desired to undesired signal ratio

3. Analog FM performance in the presence of IBOC DAB signals

USADR modeled a typical automobile FM stereo receiver. Simulation results and conclusions presented herein are based on performance of this receiver.

a. Effects of IBOC digital sidebands on analog host FM performance

*Main audio channel performance*

Results indicate that the audio noise level increases with the deviation of the FM signal. Although these results are intriguing, they do not predict degradation in host FM audio quality due to IBOC DAB. Because the DAB-induced post-detection noise floor increases in proportion to the deviation of the FM signal, the effect is self-masking: audio noise will be lowest during quiet passages, and highest only when the audio is loudest. The FM IBOC DAB signal was shown to induce an SNR of better than 77 dB in the simulated receiver during quiet passages. Since implementation constraints often limit receiver SNRs below 60 dB,[68] this should render DAB-induced audio noise imperceptible to the listener. Actual performance will depend on receiver implementation, signal strength, and ambient environment.

*SCA performance*

USADR ran simulations to determine the impact of subcarriers (SCAs) on IBOC DAB host FM performance, and to determine the impact of DAB on the performance of SCAs. Simulations indicate that a 92-kHz SCA reduces the host FM audio SNR from approximately 77 to 70 dB; however, this noise level is still too low to produce audible effects in the modeled

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68 Tests were conducted on five common receivers, and found the limiting SNR to be 59 dB on average. *See* Electronics Industries Association, "Digital Audio Radio Laboratory Tests Transmission Quality Failure Characterizations and Analog Compatibility" (Aug. 11, 1995).

receiver. Simulated SCAs located at 67 kHz were found to have even less impact on audio performance. IBOC simulations indicate that the SNR of a 67-kHz SCA (in a 10-kHz bandwidth) is 25-30 dB near the transmitter, while for 92-kHz SCAs, the SNR is 20-25 dB. The increase in noise may not pose a problem for digital SCAs (e.g., Seiko and Radio Broadcast Data System), since they should be robust enough to operate at reasonably low SNRs.

*Stereo subcarrier demodulation*

To recover stereo information, the 30-kHz-wide, double-sideband amplitude-modulated left-minus-right ("L-R") signal centered at 38 kHz is demodulated using a 38-kHz local oscillator ("LO"), and subsequently filtered with a 15-kHz lowpass filter. In most receivers, the 38-kHz LO is simply a square wave, with a 38-kHz fundamental and odd harmonics at 114 kHz, 190 kHz, etc. As a result, in the absence of adequate filtering, not only is the desired L-R signal recovered, but so is any noise in the multiplex signal that lies within $\pm$15 kHz of 114 kHz (noise around 190 kHz should be filtered prior to FM detection). This noise causes a 3-dB stereo SNR degradation in inexpensive receivers which employ little or no post-detection protection (car radios have not exhibited this problem). This 3-dB stereo SNR degradation increases when IBOC DAB is added to the analog FM signal. Simulations using the modeled typical automobile FM stereo receiver show that judicious DAB placement and pulse shaping limit the overall stereo noise increase caused by the addition of DAB in radios with inadequate filtering. In a typical ambient environment, with inexpensive receivers, it is possible that any degradation will be imperceptible to the listener.